THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

IN

MACHINE AND VEHICLE SYSTEMS

# Female and Male Whole Spinal Alignment and Cervical Kinematic Responses in Rear Impacts

FUSAKO SATO

Division of Vehicle Safety
Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
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FUSAKO SATO



THESIS FOR LICENTIATE OF ENGINEERING no 2017:04

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31-772 1000

Chalmers Reproservice
Gothenburg, Sweden, 2017

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FUSAKO SATO
Division of Vehicle Safety, Department of Mechanics and Maritime Sciences
Chalmers University of Technology

## Abstract

The susceptibility of women to Whiplash Associated Disorders (WADs) has been the focus of numerous epidemiologic studies. Summarising the epidemiologic WAD studies, women were found to be at three times higher risk of sustaining WADs than men. Analysis of insurance claims records indicate that certain whiplash protection seats have reduced the risk of sustaining WADs more effectively for men than for women. However, many aspects of WADs are still unknown, including what role gender differences play in the risk of sustaining WADs.

In order to obtain fundamental knowledge to understand the gender difference involved in the risk of sustaining WADs, this thesis reanalysed previous rear impact sled test series comprising female and male volunteers to clarify the dynamic characteristics of inertia-induced cervical vertebral kinematics during rear impacts for women and men. Furthermore, cervical spinal alignment has been suggested as one of several possible causes of the gender differences seen in the risk of sustaining WADs. In addition, it has been reported that the initial position of the thoracolumbar spine against a seatback affects vertebral kinematics as well as the cervical spine. Therefore, this study also investigated whole spinal alignments in one automotive seated posture using an upright open MRI system for both genders, and estimated average gender specific spinal alignment patterns.

During rear impacts, the female subjects presented with a more pronounced S-shape in the cervical spine than the male subjects, beyond the voluntary muscle-induced cervical kinematics range for female subjects. In contrast, for the male subjects, the peak S-shape appeared within the voluntary muscle-induced cervical kinematics range. The estimated average spinal alignment pattern in the automotive seated posture was slight kyphotic, or almost straight cervical spine with less-kyphotic thoracic spine for the female subjects, and lordotic cervical spine with more pronounced kyphotic thoracic spine for the male subjects. The findings support previous studies which have indicated influences of cervical spinal alignment on cervical vertebral kinematics. Potential impacts of any gender differences in whole spinal alignment on cervical vertebral kinematics can be investigated with a whole-body human finite element model in future work based on this thesis.

KEYWORDS: whiplash, neck injury, rear impact, cervical vertebral kinematics, automotive seated posture, spinal alignment, MRI, Multi-Dimensional Scaling, volunteer, female

# ACKNOWLEDGEMENTS

This study was conducted at the Division of Vehicle safety, Department of Mechanics and Maritime Sciences, Chalmers University of Technology in Gothenburg, Sweden, and the Crash Safety Research Group, Safety Research Division, Japan Automobile Research Institute (JARI) in Tsukuba, Japan, in a collaborative research project between Chalmers and JARI.

There are many people who have helped and supported me with this study. This study could not have been carried through without you. I would like to thank all of you:

My supervisors at Chalmers, Mats Svensson, Karin Brolin, and Jonas Östh, for your advice and continuous support, and for having me over at Chalmers. My stay in Gothenburg was a precious and very fun experience in my life.

My supervisors at JARI, Kunio Yamazaki, Tatsuo Fujikawa and Masao Nagai, for giving me the great opportunity to be involved in collaborative research with Chalmers, and for believing in me.

My project colleagues, Shigehiro Morikawa, Harumi Iguchi and Masahiro Yoshimura at Shiga University of Medical Science, Antonio Ferreiro Perez and Havier Montero at Fundación de Investigación HM Hospitales, Jacobo Antona-Makoshi and Taichi Nakajima at JARI, Sylvia Schick at Ludwig-Maximilians-Universitaet Muenchen Institute of Legal Medicine, for obtaining image data by upright open MRI systems. Makiko Kouchi, Yuko Kawai and their colleagues at AIST, and Beatriz Nácher Fernández and her colleagues at Instituto de Biomecánica de Valencia for measuring body sizes. Moreover, Yusuke Miyazaki and Mamiko Odani at Tokyo Institute of Technology for your help and support with the analyses of spinal alignment by MDS. Koshiro Ono at JARI and Koji Kaneoka at Waseda University for providing rear impact sled test data and your knowledge. It was valuable team work.

Elisabet Agar for the English language editing of this thesis.

My colleagues at the Vehicle Safety Division, Chalmers and SAFER, and at JARI for the assistance, encouragement and all the daily small chats.

My colleagues, Mitsuru Ishii, Hiroyuki Kobari and Atsuhiro Konosu at JARI for pushing me and great support. It would not have been possible to win such big funding without you.

Lastly, very special thanks to my family, friends and cats for your support and understanding.

Fusako Sato
May 2017
Gothenburg, Sweden

# List of Appended Papers

## Paper I

Sato F, Nakajima T, Ono K, Svensson MY, Brolin K and Kaneoka K (2014)
Dynamic Cervical Vertebral Motion of Female and Male Volunteers and Analysis of its Interaction with Head/Neck/Torso Behaviour during Low-Speed Rear Impact
In: *Proceedings of International Research Council on the Biomechanics of Injury (IRCOBI) Conference*, Berlin, Germany, pp. 227-249
Division of work between authors: Sato made the outline of this study. Ono and Kaneoka provided data from previous volunteer test series. Sato reanalysed and presented all data included in the paper with the help of Nakajima. The paper was written by Sato, and reviewed by all authors.

## Paper II

Sato F, Nakajima T, Ono K, Svensson MY and Kaneoka K (2015)
Characteristics of Dynamic Cervical Vertebral Kinematics for Female and Male Volunteers in Low-Speed Rear Impact, based on Quasi-Static Neck Kinematics
In: *Proceedings of International Research Council on the Biomechanics of Injury (IRCOBI) Conference*, Lyon, France, pp. 261-277
Division of work between authors: Sato made the outline of this study. Ono and Kaneoka provided data from previous volunteer test series. Sato reanalysed and presented all data included in the paper with the help of Nakajima. The paper was written by Sato, and reviewed by all authors.

## Paper III

Sato F, Odani M, Miyazaki Y, Nakajima T, Antona-Makoshi J, Yamazaki K, Ono K, Svensson M, Östh J, Morikawa S, Schick S and Ferreiro-Perez A (2016)
Investigation of Whole Spine Alignment Patterns in Automotive Seated Posture using Upright Open MRI Systems
In: *Proceedings of International Research Council on the Biomechanics of Injury (IRCOBI) Conference*, Malaga, Spain, pp. 113-130
Division of work between authors: Sato made the outline of this study. Sato, Morikawa, Ferreiro-Perez, Nakajima, Antona-Makoshi, Schick, Svensson and Östh conducted the MRI scans. Sato, Odani and Miyazaki jointly analysed and presented all data included in the paper. The paper was written by Sato, and reviewed by all authors.

# ACRONYMS AND DEFINITIONS

| | |
|---|---|
| C1–C7 | Cervical vertebrae numbered from the atlas (C1) in the caudal direction |
| CT | Computed Tomography |
| FE | Finite Element |
| L1–L5 | Lumbar vertebrae numbered in the caudal direction |
| MDS | Multi-Dimensional Scaling |
| MRI | Magnetic Resonance Imaging |
| OC | Occipital Condyle |
| PMHS | Post Mortem Human Subject |
| T1–T12 | Thoracic vertebrae numbered in the caudal direction |
| WAD | Whiplash Associated Disorder |

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# 1 INTRODUCTION

The susceptibility of women to Whiplash Associated Disorders (WADs), sustained in vehicle crashes, has been the focus of numerous epidemiological studies (Narragon 1965, Kihlberg 1969, O'Neill et al. 1972, Thomas et al. 1982, Otremski et al. 1989, Maag et al. 1990, Morris and Thomas 1996, Dolinis 1997, Temming and Zobel 1998, Chapline et al. 2000, Richter et al. 2000, Krafft et al. 2003, Jakobsson et al. 2004, Storvik et al. 2009, Carstensten et al. 2012). Summarising the above epidemiological studies (Carlsson et al. 2010), injury statistical data reveal that the risk of sustaining WADs is approximately 1.5 to 3 times higher for women than men, even in similar crash conditions. In addition, gender is a significant factor as the recovery time for women is longer than for men after sustaining WADs (Harder et al. 1998, Cassidy et al. 2000).

WADs are more commonly caused by rear impacts than in any other type of automobile impact, even though they occur in impacts from all directions (Watanabe et al. 2000; Krafft et al. 2002). As a preventive measure for WADs in rear impacts, cars have been equipped with several types of advanced whiplash protection seat concepts since the late 1990s (Jabobsson et al. 1997, Wiklund et al. 1997, Lundell et al. 1998, Sekizuka et al. 1998). According to insurance claims records, several whiplash protection seats have indeed reduced the risk of sustaining WADs, however they have proved more effective for men than women (Kullgren et al. 2010 and 2013). Therefore, in order to prevent WADs more effectively for females as well as males, further investigation to reveal gender differences in the injury mechanisms of WADs is needed.

Based on the above, this thesis focused on female and male dynamic characteristics of cervical kinematics during rear impacts, obtaining fundamental knowledge to understand gender differences in the risk of sustaining WADs. This chapter outlines the current status on WAD biomechanics studies and the aims of this thesis.

## 1.1 Whiplash Associated Disorder

Symptoms associated with WADs and their severity are diverse. Patients sustaining WADs predominantly complain of neck pain, headache, and stiffness around the neck, shoulder and upper back symptoms, frequently concomitant with other symptoms such as loss of mobility of the cervical spine, pain in other parts of the body, neurological signs like tingling and numbness, dizziness, fatigue, as well as emotional disturbances such as anxiety and depression, unconsciousness, blurred vision, etc., (Nygren et al. 1985, Deans et al. 1987, Kenna and Mutagh 1989, Watkinson et al. 1991, Evans 1992, Radanov et al. 1995, Spitzer et al. 1995, Sturzenegger et al. 1995, Starling 2004, Sterner et al. 2004, Carroll et al. 2008, Holm et al. 2008). WADs are generally considered to be soft tissue injuries of the neck. However, due to difficulties in diagnosing soft tissue damage through current medical imaging techniques including X-rays, computed tomography (CT), and magnetic resonance imaging (MRI), the aetiology of symptoms frequently remain undetected and consequently the injury mechanisms of WADs have not been fully elucidated (Davis et al. 1991, Pettersson et al. 1994, 1997, Barnsley et al. 1995, Ronnen et al. 1996, Wilmink et al. 2001, Uhrenholt et al. 2002, Krakens et al, 2002, 2003ab and 2006, Kaale et al. 2005ab, Elliott et al. 2006 and 2008ab, Binder et al 2007, Myran et al. 2008, Ichihara et al. 2009, Lindgren et al. 2009, Dullerud et al. 2010, Vetti et al. 2011, Anderson et al. 2012, Li et al. 2013). Nevertheless, experimental studies with Post Mortem Human Subjects (PMHSs) and animals have demonstrated that cervical soft tissue structures, including ligaments, facet joints and capsules, intervertebral discs, vertebral arteries, and muscles, become damaged under rear impact loading, (MacNab et al. 1964, Ommaya et al. 1968, Nibu et al. 1997, Panjabi et al. 1998a, 2004, Deng et al. 2000, Yoganandan et al. 2000 and 2001, Ivancic et al. 2004 and 2008). Autopsy studies reported similar cervical soft tissue damage as seen in the PMHS and animal experiments (Sehonstrom et al. 1993, Jonsson et al. 1994, Taylor et al. 1993 and 1996, Nibu et al. 1997).

**<u>Dynamic kinematic responses of occupants in rear impacts</u>**

During a rear impact, the torso of a properly restrained occupant starts to be pushed forward by the seatback while the head remains in situ due to inertia. At the moment of impact, the head was behind the torso, and this sudden relative displacement between the head and the torso produces a S-shape of the cervical spine. Thereafter, the head contacts the head restraint, and then the head and torso rebound from the head restraint and seat back (Matsushita et al. 1994, Siegmund et al. 1997, Davidsson et al. 1998, Deng et al. 2000, Pramudita et al. 2007, White et al. 2009, Carlsson et al. 2011). During the cervical S-shape phase, cervical segments are exposed to flexion in the upper cervical spine and to extension in the lower cervical spine (Svensson et al. 1993, Grauer et al. 1997, Ono et al. 1997 and 2006, Kaneoka et al. 1999 and 2002, Luan et al. 2000, Deng et al. 2000, Cusick et al. 2001, Yoganandan et al. 2002, Stemper et al. 2003, White et al. 2009, Stemper et al. 2011). The S-shape of the cervical spine was observed only in rear impact conditions and characterised as a nonphysiologic curvature in comparison to cervical vertebral kinematics between rear impact motion and voluntary neck extension motion with a male volunteer (Ono et al. 1997). The cervical S-shape indicates nonphysiologic loads and excessive local tensile, compression and shear in the cervical soft tissues, although it must be verified with more volunteers. Hence, previous papers have hypothesised that neck injuries related to WADs might potentially be caused by the S-shape, albeit different theories on why the S-shape causes WADs have also been discussed.

## Theories of WAD injury mechanisms

Aldman et al. (1986) hypothesised that the rapid relative displacement between the head and torso, observed during rear impacts, has the ability to generate transient pressure gradients in the spinal canal which could potentially damage the spinal nerve roots, leading to symptoms associated with WAD. Experimental studies with pigs demonstrated such transient pressure gradients in the spinal canal during a rapid relative displacement between the head and torso (Svensson et al. 1993, Örtengren et al. 1996). A series of rear impact sled tests with PMHSs support this hypothesis (Eichberger et al. 2000).

During the S-shape of the cervical spine, in the upper cervical segments, the vertebrae rotated in flexion relative to the lower adjacent vertebra, resulting in compression at the anterior region of the intervertebral discs moving the facet joints away superiorly and posteriorly from the lower adjacent facet. On the other hand, in the lower cervical segments, the vertebrae rotated in extension relative to the lower adjacent vertebra, resulting in tension at the anterior region of the intervertebral discs and compression at the posterior region of the facet joints with the upper facet sliding posteriorly along the lower adjacent facet, especially at C5/C6 (Grauer et al. 1997, Kaneoka et al. 1999 and 2002, Deng et al. 2000, Luan et al. 2000, Pearson et al. 2004). Based on experimental simulations of rear impacts with PMHS head-neck complexes, it was hypothesised that the lower cervical segments were injured in local hyperextension during the S-shape phase prior to full hyperextension of the cervical spine (Grauer et al. 1997, Cholewicki et al. 1998, Panjabi et al. 1998abcd).

Through a sequential X-ray analysis of the cervical spine during rear impacts with male volunteers, Kaneoka et al. (1999 and 2000) hypothesised that the compression of the facet joints could cause pinching and inflame the synovial folds while the tension of the intervertebral discs which would potentially cause stretching of the anterior longitudinal ligament. If the vertebral extension is large enough it may cause damage to the articular cartilage of the facet joints or detach the discs from the vertebral rim. Rear impact sled tests with PMHS head-neck complexes also demonstrated compression of the facet joints which supports the hypothesis (Cusick et al. 2001, Yoganandan et al. 2002, Ivancic et al. 2004, Panjabi et al. 2004, Pearson et al. 2004).

Excessive strain of the facet joint capsule is another hypothesis related to facet joints (Deng et al. 2000, Luan et al. 2000, Siegmund et al. 2001, Winkelstein et al. 2000, Yoganandan et al. 2002, Yang et al. 2003, Pearson et al. 2004). In an investigation of PMHSs in rear impact sled tests, Luan et al. (2000) concluded that the facet joint capsules were dominantly stretched by shear at the lower cervical segments and flexion-tension at the upper cervical segments during the S-shape of the cervical spine conducted by Deng et al. (2000). The peak strains of the facet joint capsules occurred before the head contacted the head restraint (Deng et al. 2000). In experimental rear impact simulations with pairs of adjacent cervical vertebrae and PMHS head-neck complexes, strains of the facet joint capsules were observed beyond the subfailure injury range (Winkelstein et al. 2000, Siegmund et al. 20001, Pearson et al. 2004).

Consequently, under experimental demonstrations based on the above hypotheses, greater spinal motion produced during cervical S-shape in a very short space of time, is generally considered related to soft tissue injury and a considerably increased risk of sustaining WAD.

## 1.2 Gender differences in dynamic kinematic responses in rear impacts

Gender differences in dynamic kinematic responses of occupants during rear impacts have been analysed through human volunteer tests under rear impact conditions. In overall motion analyses, female volunteers tended to be exposed to greater forward accelerations of the head and T1 including more pronounced rebound motion compared to male volunteers (Szabo et al. 1994, Siegmund et al. 1997, Hell et al. 1999, Croft et al. 2002, Linder et al. 2008, Schick et al. 2008, Carlsson et al. 2010, Carlsson et al. 2012).

Some studies have attempted to analyse dynamic inertia-induced kinematic responses of cervical vertebrae during rear impact, using a cineradiography system (Matsushita et al. 1994, Ono et al. 1997, 1999 and 2006, Kaneoka et al. 1999 and 2002, Pramudia et al. 2007). Sequential X-ray images of the cervical spine, obtained by a cineradiography system, showed greater intervertebral angular displacements with a more pronounced S-shape of the cervical spine for female volunteers than male volunteers in rear impact sled tests (Ono et al. 2006). PMHS head-neck complexes fitted with retro-reflective targets inserted into each vertebra also indicated such gender differences in female and male specimens in dynamic vertebral responses in rear impact sled tests (Stemper et al. 2003, Stemper et al. 2004). Nevertheless, data on inertia-induced cervical vertebral kinematics of women during rear impacts is limited, and detailed knowledge of gender differences on cervical vertebral kinematics are lacking since the above analyses on the cervical spine have mainly been carried out on male volunteers. In addition, factors causing greater intervertebral displacements for women have not been clarified.

As a comparison to muscle-induced cervical vertebral kinematics under quasi-static voluntary neck extension motion, dynamic characteristics of inertia-induced cervical vertebral kinematics in a rear impact sled test have been investigated (Ono et al. 1997). In quasi-static voluntary neck extension motion, vertebral angular displacement relative to the horizontal plane increased gradually from the lower to the upper vertebrae without cervical S-shape deformation throughout the entire time history of neck extension motion. On the other hand, in a rear impact condition, vertebral angular displacement relative to the horizontal plane was largest at C5 around the timing of the peak S-shape of the cervical spine. This comparison of cervical vertebral kinematics between dynamic and quasi-static conditions focused on one male volunteer, any gender differences in dynamic inertia-induced cervical vertebral kinematics against quasi-static muscle-induced cervical vertebral kinematics have not yet been well analysed.

In quasi-static voluntary neck bending experiments, gender differences in cervical kinematics have also been demonstrated. The total range of cervical intervertebral flexion-extension angles is greater for women than men (Lind et al. 1989, Youdas et al. 1992, Yukawa et al. 2012), while the total range of cervical intervertebral retraction-protrusion displacements is less for women than men (Hanten et al. 2000). Such gender differences might also affect the fact that the risk of sustaining WADs is higher for women. Consequently, there is a need to obtain dynamic characteristics of inertia-induced cervical vertebral kinematics against quasi-static muscle-induced cervical vertebral kinematics for both genders to investigate any gender differences related to the risk of sustaining WADs.

## 1.3 Anatomical gender differences of the cervical spine

In general, the anthropometrical dimensions of the neck and geometry of the cervical vertebrae are smaller for women than men (Stemper et al. 2011). In neck anthropometry, the neck circumference is less for women, while the differences in head circumference is negligible between the genders (Vasavada et al. 2001, Valkeinen et al. 2002, Harty et al. 2004, Mordaka 2004), even in comparison to size matched men based on neck length, seated height, and stature (DeRosia 2008, Vasavada et a. 2008). In cervical vertebral geometry, height, depth and width of the vertebral bodies are significantly smaller in women than men (Katz et al. 1975, Liguoro et al. 1994, DeRosia 2008, Stemper er al. 2008 and 2009), and the ratio of the vertebral body height divided by depth is smaller in women than men (Hukuda and Kojima 2002, Frobine et al. 2002, Vasavada et al. 2008). In a paper compiling previous studies (Brolin et al. 2015), the cervical vertebral height, depth and width for women is 86-98% of the measurements for men in size matched volunteers based on both neck length and standing height, and 86-95% of men in size matched volunteers with regard to seated height, head circumference, and stature. Thus, neck and smaller vertebral bodies in women are narrower than in men, indicating less support area of the neck and cervical spinal region.

The variations in alignment of cervical vertebrae (cervical spinal alignment) (Figure 1) also show gender differences. In an asymptomatic population measured in an upright seated position, cervical lordotic alignment was observed in the majority, and non-lordotic alignment was observed in 36%

(Matsumoto et al. 1998) and 38% (Takeshima 2002). Women are more likely to present non-lordosis (kyphotic or straight) than men, while men statistically present more pronounced lordosis (Helliwel 1994, Haedacker et al 1997, Matsumoto 1999). Gender is an independent factor significantly correlating with non-lordotic alignment. In an investigation of the relationship between cervical spinal alignment and stature, tall women tended to present straight alignment more frequently compared to short women, while there is no significant relationship between stature and curvature for men (Klinich et al 2004). In line with this, cervical facet joint angles have also been investigated (Milne 1991, Boyle et al. 1996, Kasai et al. 1996, Parenteau et al. 2013). However, small and inconsistent gender differences were indicated. The cervical spinal alignment and/or posture may affect the facet joint angles.

In addition, at the cervicothoracic junction, the thoracic inlet defined as the angle between the lines from the top of the manubrium to the centroid of the cranial T1 end plate and the horizontal plane, inclined further forward for men than women due to a thicker thoracic cage for men compared to women (Lee et al. 2014). A forward-inclined thoracic inlet was associated with pronounced cervical lordosis, while a smaller anteroposterior diameter of the upper thoracic cage was associated with cervical hypolordosis. These findings observed at the cervicothoracic junction are consistent with the trend of cervical spinal alignment in both genders.

In gender-dependent anatomical differences described above, Kitagawa et al (2015) focused on the size of the neck and vertebrae. With average male and female size whole-body human finite element (FE) models, rear impact simulations were conducted. The same cervical spine FE model was installed into both the male and female models, but scaled by approximately 0.86 for the female model to fit the average female size. Size differences of the neck and vertebrae in both genders affected gender differences in cervical spine motion rather than muscular strength. Despite such a simplistic approach the series of rear impact simulations pointed out that the size of the neck and vertebrae was one of key factors to be taken into account to investigate influences of the gender-dependent anatomical differences on WAD injury mechanisms.

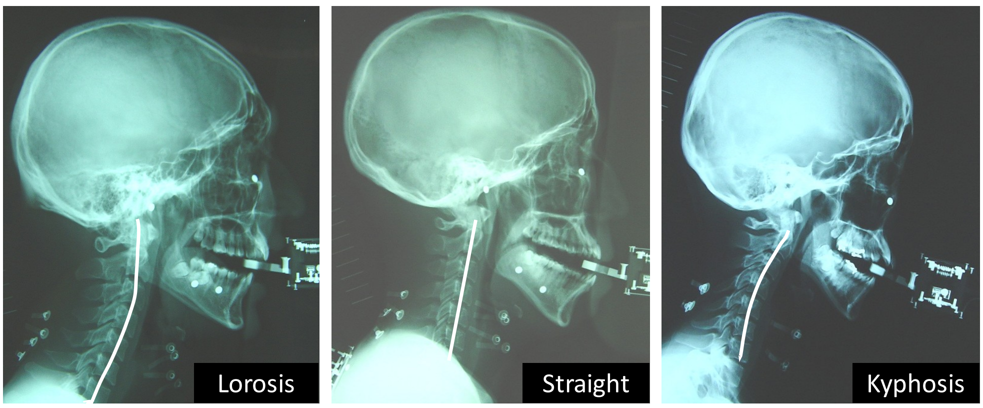


Figure 1. Variations in the cervical spinal alignment. Image data from the data set of the rear impact sled tests in Paper I and II

## 1.4 Effects of spinal alignment in rear impacts

In the gender-dependent anatomical differences described in the preceding section, cervical spinal alignment has been considered as one of the possible causes of gender differences in dynamic inertia-induced vertebral kinematics observed in rear impact sled tests with female and male subjects. Due to load transmission between the head and the torso through the cervical spine, cervical spinal alignment can affect vertebral kinematics during impact.

Experimental investigations with PMHS head-neck complexes have demonstrated that the initial cervical spinal alignment affect the severity of neck injuries (Maiman et al. 1983 and 2002, Yoganandan et al. 1986, Liu and Dai 1989, Pintar et al. 1995, Yoganandan et al. 1999,). A series of rear impact sled tests with one male volunteer showed that cervical vertebrae in kyphotic cervical spinal alignment rotated significantly more than cervical vertebrae in lordotic cervical spinal alignment (Ono et al. 1997). In a series of rear impact computer simulations (Stemper et al. 2005), the influence of initial cervical spinal alignment was investigated with a mathematical head-neck model as to elongation of the facet joint capsular ligaments in lordotic, straight and kyphotic cervical spinal alignment. Kyphotic cervical spinal alignment was exposed to larger elongation of the facet joint capsular ligaments than lordotic or straight cervical spinal alignment. As women are more likely than men to present non-lordotic cervical spinal alignment (Helliwel 1994, Haedacker et al 1997, Matsumoto 1999), described in the preceding section, such a gender difference of cervical spinal alignment implies that women may inherently be at a higher risk of WADs.

Human volunteer sled tests have also demonstrated influences of the interaction between the torso and seatback on cervical vertebral kinematics during rear impacts and its importance when investigating potential WAD producing mechanisms (Ono et al. 1999). In rear impact reconstruction simulations with a whole-body human FE model, cervical vertebral kinematics were affected by the initial position of the cervical spine as well as the thoracolumbar spine against the seatback (Sato et al. 2010). As shown in previous studies the initial spinal alignment, not only for the cervical spine but also for the thoracolumbar spine through C2 to the sacrum, resting against a seatback is therefore one of the essential key factors for further investigation into WAD injury mechanisms. However, the whole spinal alignment in automotive seated postures has not been well documented, particularly not for females (Chabert et al. 1998), generally due to the lack of available image data in supine (Parenteau et al. 2014) or standing postures (Jassen et al. 2009). Consequently, detailed knowledge of gender differences of the whole spinal alignment in automotive seated postures is lacking

In a pilot study to investigate whole spinal alignment in a seated posture (Sato et al. 2015), the intervertebral angles from C2 through to the sacrum showed different trends, even in the thoracic region when comparing a seated posture to a supine posture. In a comparison of the cervical spinal alignment between seated upright and inversed (Newell et al. 2014), the spinal alignment was influenced by the orientation of gravity. To investigate spinal alignment in a seated posture, it was therefore essential to expose volunteers in a seated posture to appropriate orientation of gravity.

## 1.5 Aims

To obtain fundamental knowledge to gain an understanding of gender differences in the risk of sustaining WADs, this thesis focused on dynamic characteristics of cervical kinematics during rear impacts in women and men.

The specific aims of this thesis were to:

- Clarify the dynamic characteristics of inertia-induced cervical kinematic responses for women and men in rear impacts.
- Obtain representative patterns of the whole spinal alignment in one automotive seated posture, including average gender specific spinal alignment patterns.

Based on the data obtained in this thesis, future work would include an investigation into any potential impacts spinal alignment patterns have on cervical kinematic responses in rear impacts using a whole-body human FE model.

# 2 Summary of Papers

This thesis contains three papers. The overview of this study including the three papers is illustrated in Figure 2 and the papers are summarised as follows:

In Paper I and II, the previous experimental data sets of rear impact sled tests comprising female and male volunteers were reanalysed to determine dynamic characteristics of inertia-induced cervical vertebral kinematics for women and men during rear impacts.

In Paper III, image data of the spinal column, acquired with an upright open MRI system were analysed to obtain representative patterns of the whole spinal alignment in one automotive seated posture, including average gender specific spinal alignment patterns.

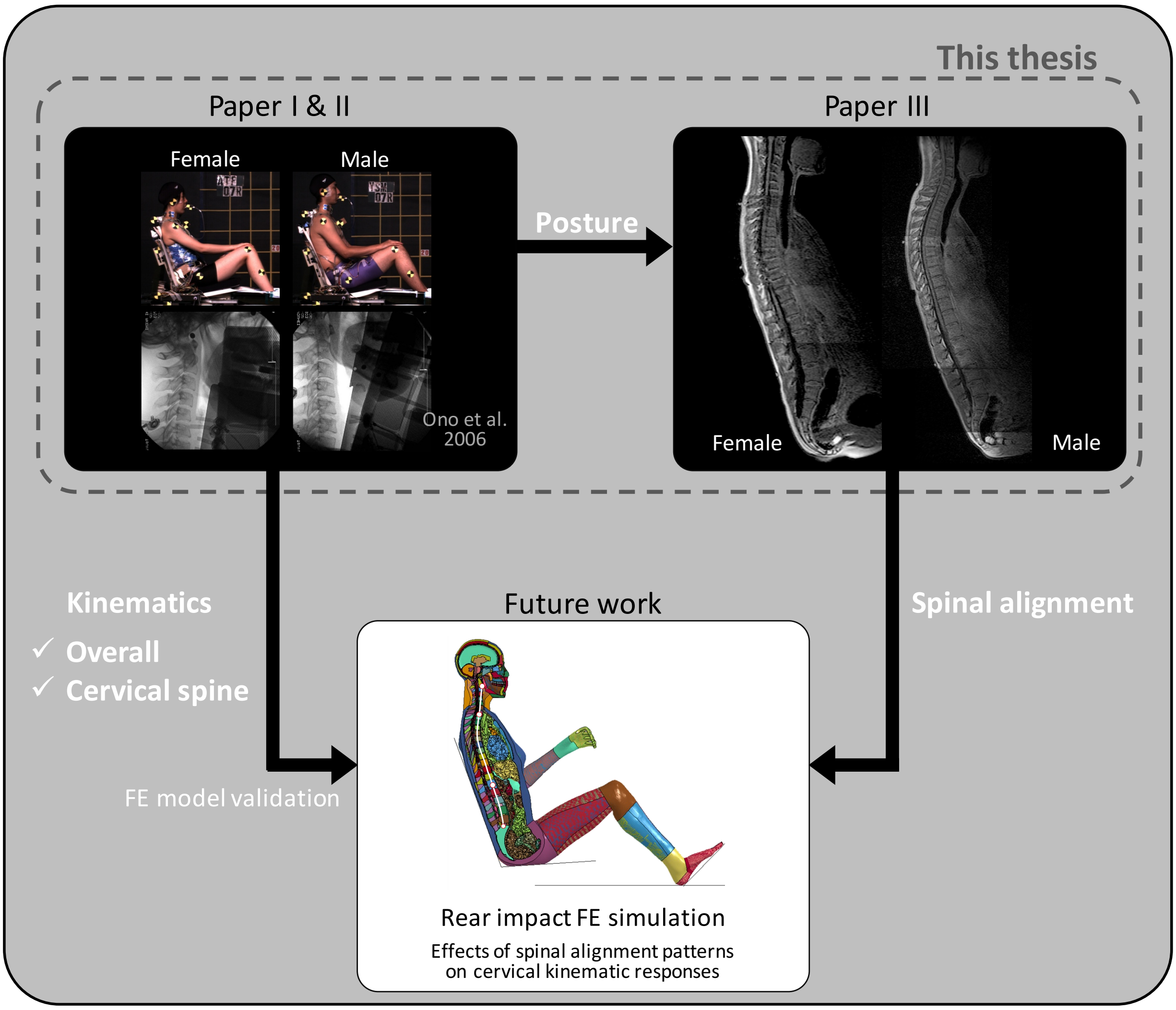


Figure 2. Overview of this study

## 2.1 Summary of Paper I and Paper II

The aim of Paper I and II was to clarify the dynamic characteristics of inertia-induced cervical kinematic responses for both women and men in low-speed rear impact conditions.

To investigate differences in dynamic inertia-induced cervical kinematic responses for women and men in rear impacts, experimental data previously obtained by rear impact sled tests with female and male volunteers (Ono et al. 2006) were reanalysed in Paper I. The main focus of that study was the peak values of strain at the facet joint capsules while gender differences of cervical vertebral kinematics were not well reported. The female and male volunteers participating in the sled tests were also subjected to quasi-static neck bending tests to quantify muscle-induced cervical vertebral kinematics. However, the results of the quasi-static neck bending tests have not been published yet. Hence, in Paper II, the muscle-induced cervical vertebral kinematics were reanalysed using the aforementioned data, and compared to the inertia-induced cervical vertebral kinematics to clarify the dynamic characteristics for both women and men.

**Methods in Paper I:** Two series of rear impact sled tests comprising female and male volunteers were reanalysed to investigate gender differences of inertia-induced cervical kinematic responses. The first one, an inclined-sled test series with 12 male subjects which is presented in Ono et al. (1997 and 1999), and eight female subjects which has not been previously published. Overall kinematics was captured by high-speed video camera. The other is a mini-sled test series with four male and two female subjects, conducted by Ono et al. (2006). Sequential X-ray images of cervical vertebrae were acquired by a cineradiography system as well as overall kinematics through a high-speed video camera. In both rear impact sled test series, a laboratory seat consisting of two rigid planes with a seatback inclined by 20 degrees from the vertical level was used, respectively. Due to the limited number of subjects in the second test series, general characteristics of inertia-induced overall head, neck and T1 responses were complemented with the first test series. Thereafter, inertia-induced cervical kinematic responses were analysed with X-ray sequential images.

**Methods in Paper II:** The inertia-induced cervical kinematic responses obtained in the second sled test series in Paper I was compared to quasi-static muscle-induced cervical kinematics in voluntary neck bending motions. The voluntary quasi-static neck bending test series which remain unpublished was conducted in the same period as the second sled test series in Paper I, comprising four male and two female subjects, and an additional five male and two female subjects; a total of nine male and four female subjects. The quasi-static muscle-induced cervical kinematics in maximum neck extension, flexion and retraction motion were obtained from sequential X-ray images of cervical vertebrae acquired by a cineradiography system.

**Results in Paper I:** Findings in Paper I are summarised in Figure 3. For overall kinematics, the female subjects exhibited peak flexion of the head relative to the neck link, defined as a line between T1 and the occipital condyle, while the neck link rotated in extension at the time of the peak flexion of the head relative to the neck link (Figure 3). On the other hand, the male subjects exhibited flexion in both the head relative to the neck link and neck link relative to T1 up to 100ms. For cervical vertebral kinematics, close to the time of peak flexion of the head relative to the neck link, the cervical spine was exposed to the peak S-shape in both female and male subjects. The female subjects exhibited greater intervertebral angles in both flexion at the upper cervical segments and extension at the lower cervical segments than the male subjects, when exposed to a more pronounced S-shape. The overall kinematics corresponded to the cervical vertebral kinematics, and supports the cineradiography data.

**Results in Paper II:** When comparing the peak cervical S-shape observed in the dynamic inertia-induced cervical vertebral kinematics to the maximum voluntary retraction, C4/C5 through C6/C7 at the peak S-shape rotated greater for the female subjects in extension than at the maximum voluntary retraction. In contrast, for the male subjects, the peak S-shape was in the range of maximum voluntary retraction. In addition, the normalised rearward displacements of C6/C7 at the peak S-shape exceeded the maximum voluntary extension for the female subjects. When looking at the peak cervical extension observed in the dynamic inertia-induced cervical vertebral kinematics, the vertebral angular displacement at C5/C6 was the greatest and exceeded the voluntary extension, especially for the female sbjects. The normalised rearward displacements of C5/C6 and C6/C7 in the X-direction exceeded the maximum voluntary extension for both genders.

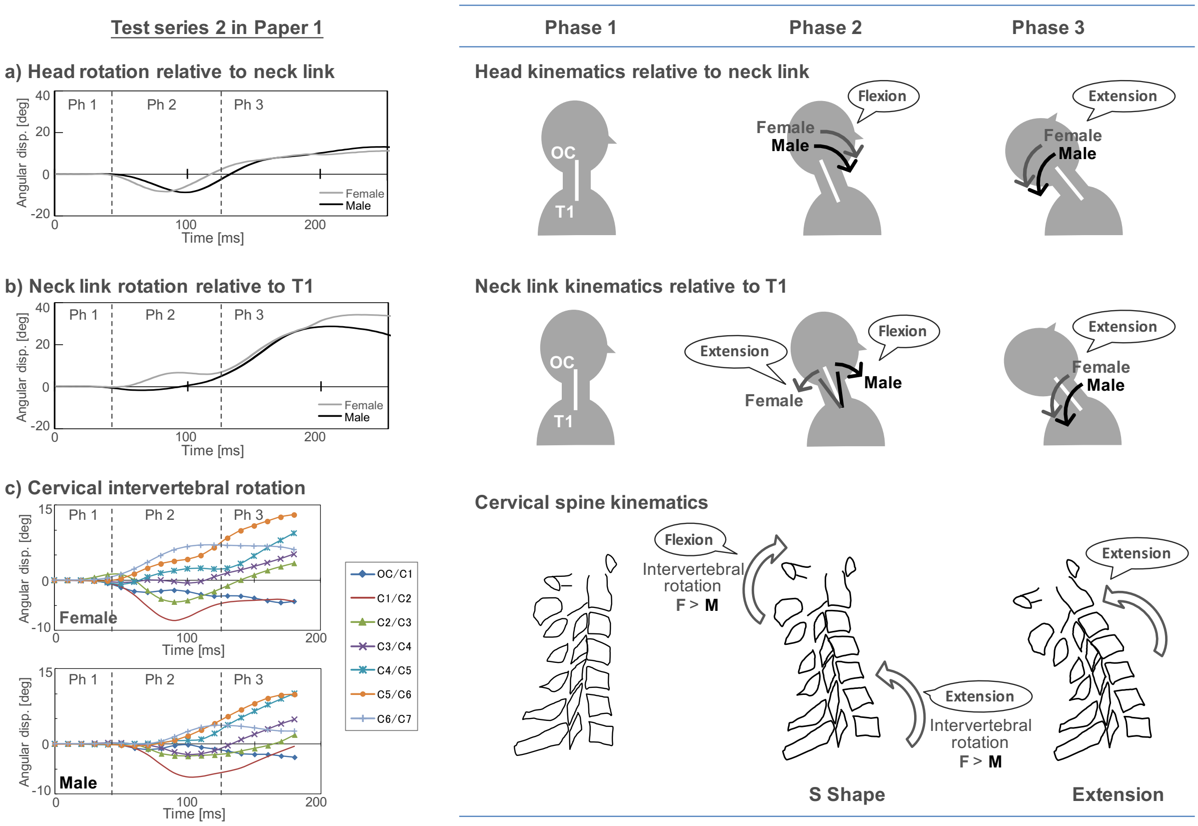


Figure 3. Time histories of the head, neck link and intervertebral angular displacement, and schematic of overall and vertebral kinematics during a rear impact. The neck link is defined as the line from the centre of T1 to the centre of OC. The positive side is extension and the negative is flexion. Time histories were divided into three phases based on the head rotation relative to the neck link shown in (a): Phase1 - remaining in the initial position, Phase 2 - rotating in flexion, and Phase 3 - rotating in extension.

## 2.2 Summary of Paper III

The aim of Paper III was to determine representative patterns of the whole spinal alignment in one automotive seated posture, including average gender specific spinal alignment patterns.

**Methods in Paper III:** Image data of the spinal column in one seated posture were acquired for eight female and seven male volunteers by an upright open MRI system. A non-metallic wooden seat, designed to correspond to the seat of the second sled test series in Paper I, was installed in a MRI system. Subjects were seated as per the procedure in the second sled test series in Paper I. The whole spinal alignment defined with the centres of the vertebral bodies from C2 to the sacrum was extracted from the image data. Each spinal alignment was rotated and normalised so that C2 was located at 1 on the normalised z-axis and the sacrum at the origin. Then, patterns of whole spinal alignments were investigated through Multi-Dimensional Scaling (MDS), a statistical method for high-dimensional data facilitating visualisation of similarities of objects in reduced data dimensions, generally two or three dimensions less. A distance matrix applied as the input data for MDS consisted of all possible inter-individual distances between two subjects, defined as the sum of squared Euclidean pairwise distances between corresponding vertebrae. By applying MDS to the distance matrix, a two-dimensional distribution map of the whole spinal alignment was obtained. On the distribution map, representative whole spinal alignments for all subjects were estimated at the intersections of the 50% probability ellipsoid and the axes of the 1$^{st}$ and 2$^{nd}$ MDS dimensions by the weighted average of all whole spinal alignments. Average whole spinal alignments for female and male subjects were also estimated at the average point on the distribution map, respectively.

**Results in Paper III:** On the distribution map of whole spinal alignments, the maximum variance of whole spinal alignments (the 1$^{st}$ MDS dimension) illustrated that whole spinal alignments tended to shift the combination from kyphotic cervical and less-kyphotic thoracic spine with a peak of the thoracic kyphosis at a higher vertebral level, to lordotic cervical and more pronounced kyphotic thoracic spine with a peak of the thoracic kyphosis at a lower vertebral level. The peak of the thoracic kyphosis means the most rearward vertebra of the thoracic spine. The 2$^{nd}$ maximum variance of the whole spinal alignments (the 2$^{nd}$ MDS dimension) illustrated that the thoracolumbar spine tended to shift from rearward to forward. These trends were observed in the representative spinal alignments estimated at the intersections of the 50% probability ellipsoid and the axes of the 1$^{st}$ and 2$^{nd}$ MDS dimensions, shown in Figure 4. The estimated average spinal alignment for each gender, shown in Figure 5, portrayed the variation indicated in the 1$^{st}$ MDS dimension because of the average MDS score of the 2$^{nd}$ MDS dimension was close to zero for both genders. The estimated average spinal alignment pattern was slightly kyphotic, or almost straight cervical and less-kyphotic thoracic spine for the female subjects, and lordotic cervical and more pronounced kyphotic thoracic spine for the male subjects.

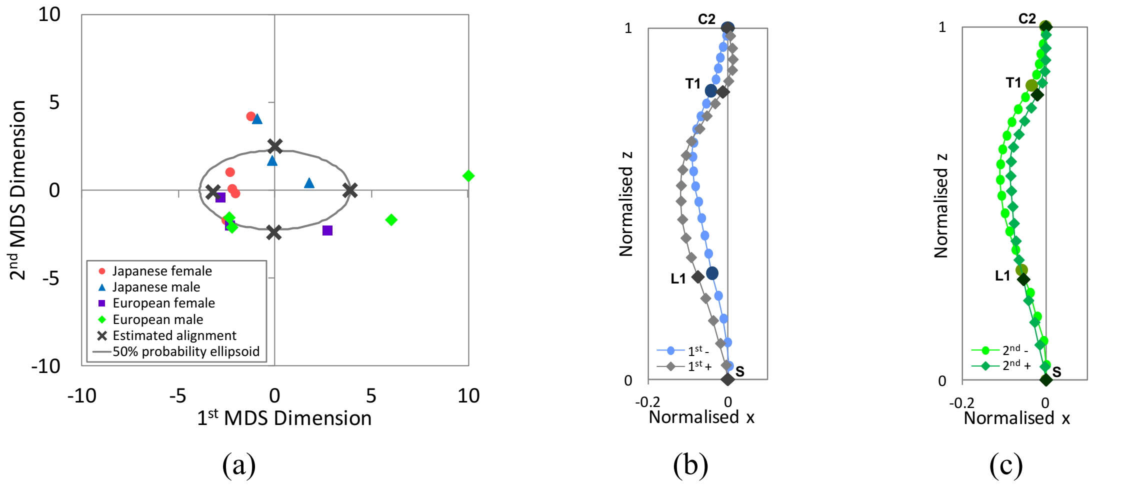


Figure 4. Two-dimensional distribution map for whole spinal alignments with the 50% probability ellipsoid (a) and representative whole spinal alignment patterns estimated on the 50% probability ellipsoid (b)(c). ‘1st -‘ and ‘1st +’ indicate the representative spinal alignment patterns estimated at the intersection of the 50% probability ellipsoid and the axes of the 1st MDS dimension in the negative and positive regions of the 1st MDS dimension, respectively. ’2nd -‘ and ’2nd +’ indicate the representative spinal alignment patterns estimated at the intersection of the 50% probability ellipsoid and the axes of the second MDS dimension in the negative and positive regions of the second MDS dimension, respectively. The spinal alignments were rotated and normalised so that C2 was located at 1 on the normalised Z-axis with the sacrum at the origin. The right side of chart (b) and (c) represent the abdominal side and the left side of chart (b) and (c) represent the dorsal side.

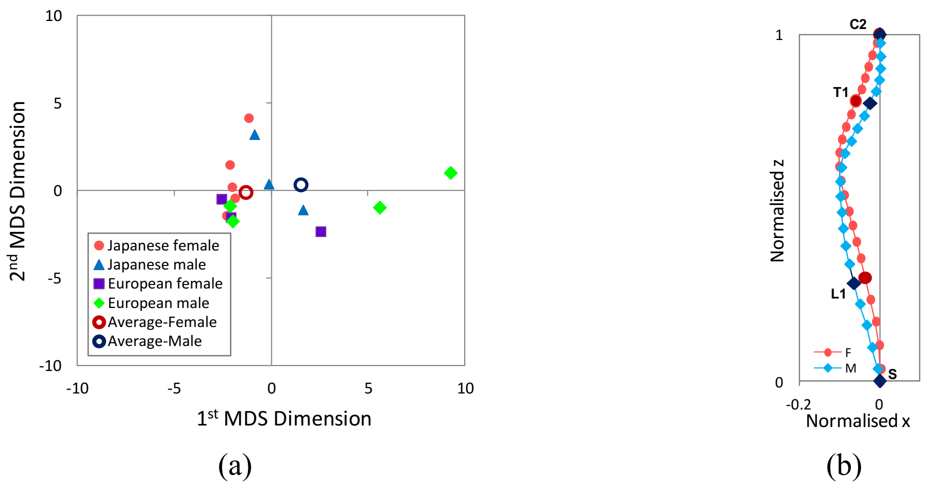


Figure 5. Two-dimensional distribution map for whole spinal alignments with the average MDS score for the female and male subjects (a) and whole spinal alignment patterns estimated on the average MDS score for the female and male subjects (b). ‘F’ and ‘M’ indicate spinal alignments estimated at the average MDS score for female and male subjects, respectively. The spinal alignments were rotated and normalised so that C2 was located at 1 on the normalised Z-axis with the sacrum at the origin. The right side of chart (b) represents the abdominal side and the left side of chart (b) represents the dorsal side.

# 3 DISCUSSION

During rear impact, the female subjects were exposed to a more pronounced S-shape in the cervical spine than the male subjects, beyond their range of voluntary muscle-induced cervical kinematics for the female subjects, as described in Paper I and II. In Paper III, the estimated average spinal alignment pattern in an automotive seated posture corresponding to the posture in the rear impact sled tests was slight kyphotic, or almost straight cervical and less-kyphotic thoracic spine for the female subjects, and lordotic cervical and more pronounced kyphotic thoracic spine for the male subjects.

Previous studies have demonstrated influences of initial cervical spinal alignment on the cervical spine motion and the severity of neck injury (Maiman et al. 1983 and 2002, Yoganandan et al. 1986 and 1999, Liu et al. 1989, Pintar et al. 1995, Ono et al. 1997, Stemper et al. 2005). Kyphotic cervical spinal alignment indicated greater vertebral rotations and larger elongation of the facet joint capsular ligaments than lordotic cervical spinal alignment during a rear impact (Ono et al. 1997, Stemper et al. 2005). In this study, the estimated average spinal alignment for the female subjects illustrated slight kyphotic, or almost straight cervical spine, while lordotic cervical spine for the male subjects. Then, the female subjects showed greater intervertebral angular and translational displacements with a more pronounced S-shape of the cervical spine than the male subjects. The findings in this study are in line with previous findings (Ono et al. 1997, Stemper et al. 2005). Hence, the female cervical spinal alignment trend may make women exposed to larger elongation of the facet joint capsular ligaments due to greater intervertebral displacements during a rear impact and thus increase the risk of women sustaining WADs.

Furthermore, the estimated average spinal alignment illustrated less-kyphotic thoracic spine for the female subjects than the male subjects. The MDS analysis of whole spinal alignments in this thesis portrayed a relationship trend between cervical spine and thoracic spinal alignment. The thoracic spine links to the cervical spine continuously, and external force from the seatback to the torso is transmitted to the cervical spine gradually via the thoracic spine. Thus, thoracic spinal alignment may also have a potential impact on cervical spine kinematics as well as cervical spinal alignment.

However, previous studies (Maiman et al. 1983 and 2002, Yoganandan et al. 1986 and 1999, Liu et al. 1989, Pintar et al. 1995, Ono et al. 1997, Stemper et al. 2005) have been conducted with PMHS head-neck complexes, a mathematical head-neck model or just one male volunteers. In order to clarify the influences of whole spinal alignment patterns on cervical kinematic responses in rear impacts, further investigation with human volunteers or whole-body human FE model is needed.

The seats used in this thesis were laboratory seats consisting of just two flat panels without head restraint to exclude the influence of seat properties. The seated height was thus not a factor to explain individual differences in cervical vertebral kinematics and spinal alignment, since the flatness of the seating surface made the set-up insensitive to seated height. This means that it is easier to assign differences in cervical vertebral kinematics and spinal alignment to gender, and would result in such gender differences as were observed in this thesis.

## 3.1 Cervical kinematic responses in rear end impacts

The dynamic inertia-induced cervical kinematics obtained in the second sled test series, Paper I, was compared to the quasi-static muscle-induced cervical kinematics obtained in the voluntary neck bending motions described in Paper II. In the dynamic inertia-induced cervical kinematics for both genders, until around 110 ms, OC and C1 rotated in flexion relative to C7, while other vertebrae rotated in extension. Afterwards, all vertebrae rotated in extension relative to C7. On the other hand, in the quasi-static muscle-induced cervical kinematics, all vertebrae rotated in extension relative to C7 when moving the cervical spine in voluntary neck extension and S-shape deformation was not observed. Such differences in cervical kinematics between dynamic inertia-induced and quasi-static muscle-induced responses support former studies with one male subject (Ono et al. 1997 and 1999). Therefore, the main characteristic of dynamic inertia-induced cervical kinematics is represented by the cervical S-shape, followed by the transition from the S-shape to the extension phase (Matsushita et al. 1994, Grauer et al. 1997, Yoganandan et al. 1998, Kaneoka et al. 1999, Deng et al. 2000, Luan et al. 2000, Cusick et al. 2001, Panjabi et al. 2004).

The extension of the lower cervical spine at C4/C5, C5/C6 and C6/C7 was considerably greater, while the flexion of the upper cervical spine at OC/C1, C1/C2 and C2/C3 was only slightly greater for the female subjects compared to the male subjects, in the S-shape of dynamic inertia-induced cervical kinematics during the time between 90 ms to 100 ms, when the intervertebral angular displacement at C1/C2 exhibited the greatest peak flexion angle on all intervertebral levels. The female subjects were exposed to a more pronounced peak S-shape than the male subjects. This cervical kinematic response trend is in line with the rear impact sled test series with PMHS head-neck complexes by Stemper et al. 2003 and 2004. The more pronounced S-shape indicates larger local intervertebral displacements that could cause more severe strain and loading on the facet joint capsules (Deng et al. 2000, Luan et al. 2000, Winkelstein et al. 2000, Siegmund et al. 2001, Yoganandan et al. 2002, Yang et al. 2003, Pearson et al. 2004) and higher pressure magnitudes in the spinal canal during whiplash motion (Yao et al. 2016). It has been suggested that these pressure transients produce dorsal root ganglion injuries (Örtengren et al. 1996). Therefore, the gender differences in the cervical S-shape phase could potentially become part of the explanation for the higher injury risk of women sustaining WADs.

The peak S-shape in dynamic inertia-induced cervical kinematics was compared to the voluntary neck retraction at its maximum position in the quasi-static muscle-induced cervical kinematics, since the voluntary neck retraction caused flexion in the upper vertebrae and extension in the lower vertebrae, similar to the cervical S-shape observed in the dynamic inertia-induced cervical kinematics. For the female subjects, C4/C5 through C6/C7 showed larger extension angles in the peak S-shape than maximum voluntary retraction. On the other hand, the peak S-shape was in the maximum voluntary retraction range for the male subjects. This thesis had assumed that the voluntary quasi-static muscle-induced cervical kinematics would be within a non-injurious range. It has been hypothesised that in cases where the voluntary quasi-static muscle-induced cervical kinematics range has been exceeded, that the additional vertebral displacement has the potential of being harmful (Panjabi et al. 1999). It is therefore feasible that this result partly explains the higher injury risk of women sustaining WADs.

# 3.2 Implications of actual whiplash injuries

The laboratory rigid seats used for the volunteer rear impact sled tests in Paper I were not equipped with head restraints. Previous rear impact sled tests with an automotive seat at the same impact level as in this thesis reported that head-to-head restraint contact time was 91 ms for women and 100 ms for men (Carlsson et al. 2010), and 95 ms for men (Pramudita et al. 2007). In the second sled test series in Paper I, the cervical spine was exposed to the peak S-shape at a time between 90 ms and 100ms for both genders. The cervical S-shape was more pronounced for the female subjects than the male subjects, and exceeded the range of maximum voluntary retraction motion for female subjects, as described in Paper II. Head-to-head restraint contact time depends on several factors; foam stiffness, seatback recliner stiffness, and the initial gap between the head and head restraint. However, based on findings in this thesis and the head-to-head restraint contact timings reported in previous papers (Pramudita et al. 2007, Carlsson et al. 2010), it has been found that in real-world rear impact cases at the same impact level as adopted in this thesis, the peak S-shape might occur around the head-to-head restraint contact for both women and men. Hence, women would potentially be exposed to a more pronounced S-shape than men, beyond voluntary muscle-induced cervical vertebral kinematics, and consequently a higher risk of sustaining a WAD. Considering more severe and injurious real-world accidents, it is to be expected that the vertebral kinematic responses would follow the trends observed in the sled tests, but they exceed the voluntary range of motion to an even greater extent and thus cause tissue damage. The female subjects in the second sled test series in Paper I were exposed to a more pronounced S-shape than male subjects. Similarly, in more severe and injurious real-world accidents, it is expected that women would be exposed to an even more pronounced S-shape than men. However, to avoid subjecting the volunteers to injuries in the rear impact tests, this thesis did not address the higher impact levels observed in real-world accidents. Consequently, further analysis at real-world accident impact levels is needed, whereby whole-body human FE models suitable for investigating gender differences in dynamic cervical vertebral kinematics at higher impact levels, would be powerful tools.

Investigations into the prevalence of neck pain at the cervical zygapophysial joint, sustained in rear end accidents, found that the chronic pain the majority of patients experienced occurred at

C2/C3 or C5/C6 (Barnsley et al. 1995, Lord et al. 1996, Liliang et al. 2008). The study of a rear impact sled test series with PMHSs reported that slight damage was found at the C5/C6 and C6/C7 level during the autopsy (White et al. 2009). In the volunteer rear impact sled tests in Paper I, most forward vertebral translational displacement relative to the lower adjacent vertebra was observed at C2/C3 in the female subject. At C5/C6 and C6/C7, vertebral angular displacement in extension and rearward displacement relative to the lower adjacent vertebra was observed beyond the voluntary muscle-induced vertebral kinematics range, especially in the female subjects. Such findings in this thesis indicate similar vertebral levels as reported in clinical studies for the prevalence of neck pain and in the autopsy report of the PMHS sled tests. In the original report of the second sled test series in Paper I (Ono et al. 2006), three male subjects had neck or shoulder muscular pain/discomfort, or shoulder discomfort. The rear impact sled tests were conducted under relaxed conditions as well as with the muscles tensed. Tensing the muscles may induce symptoms of muscular pain/discomfort post sled tests and it was difficult to identify the aetiology of the subjects' complaints. The other subjects, including female subjects, had no complaints following the rear impact sled tests.

## 3.3 Whole spinal alignment patterns in one automotive seated posture

Through MDS analyses of whole spinal alignments in one automotive seated posture in Paper III, a prominent relationship was found between the cervical spinal alignment and the thoracic kyphosis. The combination was slight kyphotic or almost straight cervical spine with less-kyphotic thoracic spine, or lordotic cervical spine with more pronounced kyphotic thoracic spine (Figure 4b and Figure 5b).

In the cervical region, the average spinal alignment estimated in this study was non-lordotic for the female subjects and lordotic for the male subjects. At the cervicothoracic junction, the estimated average spinal alignment inclined less forward for the female subjects compared to the male subjects. As reported in previous studies on the variation in cervical spinal alignment (Helliwel et al. 1994, Haedacker et al. 1997, Matsumoto et al. 1998), gender is an independent factor which correlates significantly with non-lordosis in line with findings in Paper III. Women are more likely to present non-lordosis (kyphotic or straight). Conversely, men present more pronounced lordosis statistically (Helliwel et al. 1994, Haedacker et al. 1997, Matsumoto et al. 1998). In addition, previous studies (Lee et al. 2014, Park et al. 2015) investigated a relationship between T1 inclination and cervical spinal alignment. With decreasing T1 inclination, the cervical spinal alignment is more likely to present hypo-lordosis or kyphosis. The gender differences of the cervical spinal alignment observed in this study are in agreement with the above mentioned previous studies.

In the lumbar region, the estimated average spinal alignment showed slightly more pronounced lordosis for the female subjects when compared to the male subjects. In a report by Endo et al. (2014), the lumbar lordosis is significantly greater for women than men in the upright seated position. This study focused on one automotive seated posture instead of an upright seated posture. Subjects in this thesis were seated deeply on the rigid laboratory seat and leaned in for good contact with the flat plane seatback along the entire back. Thus, the lumbar spine was straightened along the seatback, and showed smaller gender differences of the lumbar spinal alignment compared to the upright seated posture. Differences in seated posture and gender might affect the degree of lumbar lordosis.

# 4 CONCLUSIONS

Reanalysis of previous rear impact sled test data provided dynamic characteristics of inertia-induced cervical vertebral kinematics for women and men during rear impacts. This reanalysis specified trends in the gender differences of inertia-induced cervical vertebral kinematics.

Image data acquired by an upright open MRI system showed variations in the whole spinal alignment in one automotive seated posture. The estimated average gender specific spinal alignments illustrated gender differences of whole spinal alignment in this automotive seated posture.

The gender differences found in this thesis support previous studies, and may contribute to the higher injury risk of sustaining WADs for women. Potential impacts of gender differences in whole spinal alignment on cervical vertebral kinematics will in future be investigated with a whole-body human FE model based on the work in this thesis.

The main findings on dynamic characteristics of inertia-induced cervical kinematics responses for women and men in rear impact are listed as follows:

- The dynamic inertia-induced vertebral kinematics showed a peak S-shape phase with the greatest peak flexion of C1/C2 at a time between 90 ms and 100 ms, and the transition from the peak S-shape to extension phase for both genders.
- The vertebral angular displacements in dynamic inertia-induced cervical vertebral kinematics were larger for the female subjects than the male subjects at all spinal segments virtually throughout the whole sled test duration, producing a more pronounced cervical S-shape for the female subjects.
- In the quasi-static muscle-induced vertebral kinematics, all vertebrae rotated in extension and the S-shape deformation was not observed in voluntary neck extension.
- C4/C5 through C6/C7 showed larger extension angles in the peak S-shape beyond the range observed in maximum voluntary retraction for the female subjects. In contrast, the peak S-shape for the male subjects appeared within the range of maximum voluntary retraction.

The main findings on whole spinal alignment patterns in one automotive seated posture are listed as follows:

- Subjects with lordotic cervical spinal alignment tended to have a more pronounced kyphotic thoracic spine, with a peak of the thoracic kyphosis at a lower vertebral level. Subjects with kyphotic cervical spinal alignment tended to have a less-kyphotic thoracic spine, with a peak of the thoracic kyphosis at a higher vertebral level.
- Similar trends were also observed in the differences of estimated average spinal alignment patterns between genders. The female average spinal alignment was slight kyphotic, or

almost straight cervical and less-kyphotic thoracic spine. The male average spinal alignment was lordotic cervical and more pronounced kyphotic thoracic spine. A slight gender difference was seen in the lumbar spinal alignment due to the seat design used in this thesis.

# 5 FUTURE WORK

Future work will include FE analyses based on occupant kinematics data during rear impacts and spinal alignment in one automotive seated posture obtained in this thesis, using a whole-body human FE model to investigate effects of spinal alignment patterns on cervical kinematic responses during rear impacts. Human volunteers present with individual differences and limitations in controlling spinal alignment. A further limitation is the level of ionising radiation volunteers can be exposed to for acquiring sequential images of spinal kinematics during impacts. Thus, a whole-body human FE model would be a more appropriate tool which would allow making changes to the spinal alignment while keeping other parameters unchanged, e.g., body and skeletal sizes, material properties, etc., when investigating cervical kinematic responses during impacts. In future work, the spinal alignments obtained in Paper III would be suitable for use with a whole-body human FE model. For instance, the FE model could be based on an existing model and validated against subjects in the second sled test series in Paper I. Thereafter, it would be possible to vary the model's spinal alignment in representative patterns specified in Paper III to investigate if differences in spinal alignment has the potential to contribute to differences in cervical intervertebral kinematics during rear impacts.

Further analysis is needed to access spinal alignments and kinematics of volunteers with a commercially available automotive seat at low speeds, as well as real world accident levels with a whole-body human FE model. Seat properties (foam and frame stiffness, etc.) and seat positioning (seat back angle, steering wheel placement, etc.) might affect spinal alignment and kinematics during rear impacts. In addition, other vehicle interior elements might also affect seated position and occupant posture including spinal alignment, such as different types of vehicles, variations in seat height, mirror position, steering wheel placement, etc.

In the analyses of whole spinal alignments, only the coordinates of the centre of vertebral bodies were used. The MRI data also contain 3D images of spinal cord, flesh, heart, diaphragm, stomach, etc. Information obtained from the MRI data would be suitable for further study to investigate spinal alignment in 3D and its relationship to organs and soft tissue (size, shapes and positions).

The subjects scanned by the upright open MRI system were in the 20–40 years age group and they were recruited in Europe and Japan. The selection was based on the crash test dummy family sizes (Schneider et al. 1983) for European subjects and the average height and weight of the Japanese population aged between 20-40 for Japanese subjects. Due to the cost of the MRI scans, this thesis concentrated on the average body sizes in the 20-40 age group. To generalise spinal alignment patterns for a wider range of body sizes, ages and other factors which might affect spinal alignment, additional MRI scanning is needed to further investigate whole spinal alignment.

# 6 REFERENCES


Anderson, S.E., Boesch, C., Zimmermann, H., Busato, A., Hodler, J., Bingisser, R., Ulbrich, E.J., Nidecker, A., Buitrago-Téllez, C.H., Bonel, H.M., Heini, P., Schaeren, S. & Sturzenegger M. (2012) Are there cervical spine findings at MR imaging that are specific to acute symptomatic whiplash injury? A prospective controlled study with four experienced blinded readers. *Radiology,* 262(2), 567-575.

Aldman, B. (1986) An analytical approach to the impact biomechanics of head and neck injury. In: *Association for Advancement of Automotive Medicine*, Montreal, Canada, 446–454.

Barnsley, L., Lord S.M., Wallis B.J. & Bogduk, N. (1995) The prevalence of chronic cervical zygapophysial joint pain after whiplash. *Spine*, 20(1), 20-25.

Binder, A. (2007) The diagnosis and treatment of nonspecific neck pain and whiplash. *EURA Medicophysics*, 43(1), 79-89.

Brolin, K., Östh, J., Svensson, M.Y., Sato, F., Ono, K., Linder. A. & Kullgren A. (2015) Aiming for an average female virtual human body model for seat performance assessment in rear-end impacts. In: *Enhanced Safety of Vehicles Conference*, Gothenburg, Sweden.

Boyle, J., Singer, K. & Milne, N. (1996) Morphological survey of the cervicothoracic junctional region. *Spine*, 21(5), 544-548.

Carlsson, A., Siegmund, G.P., Linder, A. & Svensson, M.Y. (2010) Motion of the head and neck of female and male volunteers in rear impact car-to-car tests at 4 and 8 km/h. In: *International Research Council on the Biomechanics of Injury Conference*, Hanover, Germany.

Carlsson, A., Linder, A., Davidsson, J., Hell, W., Schick, S. & Svensson M.Y. (2011) Dynamic kinematic responses of female volunteers in rear impacts and comparison to previous male volunteer tests. *Traffic Injury Prevention*, 12, 347–357.

Carlsson, A., Siegmund, G.P., Linder, A. & Svensson M.Y. (2012) Motion of the head and neck of female and male volunteers in rear impact car-to-car impacts. *Traffic Injury Prevention*, 13, 378–387.

Carroll, L.J., Holm, L.W., Hogg-Johnson, S., Côté, P., Cassidy, J.D., Haldeman, S., Nordin, M., Hurwitz, E.L., Carragee, E.J., van der Velde, G., Peloso, P.M. & Guzman, J. (2008) Course and prognostic factors for neck pain in whiplash-associated disorders (WAD). Results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. *European Spine Journal*, 17(Suppl 1), 83–92.

Carstensen, T.B., Frostholm, L., Oernboel, E., Kongsted, A., Kasch, H., & Jensen T.S. (2012) Are there gender differences in coping with neck pain following acute whiplash trauma? A 12-month follow-up study. *European Journal of Pain*, 16(1), 49–60.

Cassidy, J.D., Carroll, L.J. & Cote, P. (2000) Effect of eliminating compensation for pain and suffering on the outcome of insurance claims for whiplash injury. *The New England Journal of Medicine*, 342(16), 1179–86.

Chabert, L., Ghannouchi, S., & Cavallero, C. (1998) Geometrical characterisation of a seated occupant. In: *Enhanced Safety of Vehicles Conference*, Ontario, Canada.

Chapline, J.F., Ferguson, S.A., Lillis, R.P., Lund, A.K. & Williams, A.F. (2000) Neck pain and head restraint position relative to the driver's head in rear-end collisions. *Accident Analysis and Prevention*, 32(2), 287–297.

Cholewicki, J., Panjabi, M.M., Nibu, K., Babat, L.B., Grauer, J.N. & Dvorak, J. (1998) Head kinematics during in vitro whiplash simulation. *Accident Analysis and Prevention*, 30(4), 469–479.

Croft, A.C., Haneline, M.T. & Freeman, M.D. (2002) Differential occupant kinematics and forces between frontal and rear automobile impacts at low speed: evidence for a differential injury risk. In: *International Research Council on the Biomechanics of Injury Conference*, Munich, Germany.

Cusick, J.F., Pintar, F.A. & Yoganandan, N. (2001) Whiplash syndrome. Kinematic factors influencing pain patterns. *Spine*, 26(1),1252–1258.

Davidsson, J., Deutscher, C., Hell, W., Svensson, M.Y., Linder, A. & Lövsund, P. (1998) Human volunteer kinematics in rear-end sled collisions. In: *International Research Council on the Biomechanics of Injury Conference*, Gothenburg, Sweden.

Davis, S., Teresi, L., Bradley, W., Ziemba, M. & Bloze A. (1991) Cervical spine hyperextension injuries: MR findings. *Radiology*, 180(1), 245–51.

Deans, G.T., Magalliard, J.N., Kerr, M. & Rutherford, W.H. (1987) Neck sprain - a major cause of disability following car accidents. *Injury*, 18(1), 10-12.

Deng, B., Begeman, P.C., Yang, K.H., Tashman, S. & King, A.I. (2000) Kinematics of human cadaver cervical spine during low speed rear-end impacts. *Stapp Car Crash Journal*, 44, 171-188.

Deng, B., Luan, F., Begeman, P.C., Yang, K.H., King, A.I. & Tashman, S. (2000) Testing shear hypothesis of whiplash injury using experimental and analytical approaches. In: Yoganandan, N., and Pinter, F.A. (eds) Frontiers in whiplash trauma. IOS Press, Amsterdam, The Netherlands, 491–509.

DeRosia, J. (2008) *Role of gender and size in biomechanics of rear impact*. PhD. Marquette University, Texas, USA. Doctoral Dissertation, Number: 3357947.

Dolinis, J. (1997) Risk factors for “Whiplash” in drivers: a cohort study of rear-end traffic crashes. *Injury*, 28(3), 173–179.

Dullerud, R., Gjertsen, O. & Server A. (2010) Magnetic resonance imaging of ligaments and membranes in the craniocervical junction in whiplash-associated injury and in healthy control subjects. *Acta Radiologica*, 51(2), 207–212.

Eichberger, A., Darok, M., Steffan, H., Leinzinger, P.E., Boström, O. & Svensson, M.Y. (2000) Pressure measurements in the spinal canal of post-mortem human subjects during rear-end impact and correlation of results to the neck injury criterion. *Accident Analysis and Prevention*, 32(2), 251–260.

Elliott, J., Jull, G., Noteboom, J.T., Darnell, R., Galloway, G. & Gibbon, W.W. (2006) Fatty infiltration in the cervical extensor muscles in persistent whiplash-associated disorders: a magnetic resonance imaging analysis. *Spine*, 31(22), 847–855.

Elliott, J., Jull, G., Noteboom, J.T. & Galloway, G. (2008) MRI study of the cross-sectional area for the cervical extensor musculature in patients with persistent whiplash associated disorders (WAD). *Manual Therapy*, 13(3), 258–265.

Elliott, J.M. & Cherry, J. (2008) Upper cervical ligamentous disruption in a patient with persistent whiplash associated disorders. *The Journal of Orthopaedic and Sports Physical Therapy*, 38(6), 377.

Endo, K., Suzuki, H., Nishimura, H., Tanaka, H., Shishido, T. & Yamamoto, K. (2004) Characteristics of sagittal spino-pelvic alignment in Japanese young adults. *Asian Spine Journal*, 8(5), 599–604.

Evans, R.W. (1992) Some Observations on Whiplash Injuries. *Neurologic Clinics*, 10(4) 975–997.

Frobin, W., Leivseth, G., Biggemann, M. & Brinckmann, P. (2002) Vertebral height, disc height, posteroanterior displacement and dens–atlas gap in the cervical spine: precision measurement protocol and normal data. *Clinical Biomechanics*, 17(6), 423- 431.

Grauer, J.N., Panjabi, M.M., Cholewicki, J., Nibu, K. & Dvorak, J. (1997) Whiplash produces an S-shaped curvature of the neck with hyperextension at lower levels. *Spine*, 22(21), 2489-2494.

Haedacker, J.W., Shuford, R.F., Capicoto, P.N. & Pryor, P.W. (1997) Radiographic standing cervical segmental alignment in adult volunteers without neck symptoms. *Spine*, 22(13), 1472-1480.

Hanten, W.P., Olson, S.L., Russell, J.L., Lucio, R.M. & Campbell, A.H. (2000) Total head excursion and resting head posture: normal and patient comparisons. *Archives Physical Medicine and Rehabilitation*, 81(1) 62–66.

Harder, S., Veilleus, M. & Suissa, S. (1998) The effect of socio-demographic and crash-related factors on the prognosis of whiplash. *Journal of Clinical Epidemiology*, 51(5), 377–84.

Harty, J., Quinlan, J., Kennedy, J., Walsh, M. & O'Byrne, J. (2004) Anthropometrical analysis of cervical spine injuries. *Injury*, 35(3), 249-252.

Hell, W., Langwieder, K. & Walz, F. (1998) Reported soft tissue neck injuries after rear-end car collision. In: *International Research Council on the Biomechanics of Injury Conferen*ce, Gothenburg, Sweden.

Helliwel, P.S., Evans, P.F. & Wright, V. (1994) The Straight cervical spine: does it indicate muscle spasm? *The Journal of Bone & Joint Surgery*, 76(1), 103-106.

Holm, L.W., Carroll L.J., Cassidy, J.D., Hogg-Johnson, S., Côté, P., Guzman, J, Peloso, P., Nordin, M., Hurwitz, E., van der Velde, G., Carragee, E. & Haldeman S. (2008) The burden and determinants of neck pain in whiplash-associated disorders after traffic collisions. Results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. *European Spine Journal,* 17(Suppl 1), 52-59.

Hukuda, S. & Kojima, Y. (2002) Sex discrepancy in the canal/body ratio of the cervical spine implicating the prevalence of cervical myelopathy in men. *Spine,* 27(3), 250-253.

Ichihara, D., Okada, E., Chiba, K., Toyama, Y., Fujiwara, H., Momoshima, S., Nishiwaki, Y., Hashimoto, T., Ogawa, J., Watanabe, M., Takahata, T. & Matsumoto, M. (2009) Longitudinal magnetic resonance imaging study on whiplash injury patients: minimum 10-year follow-up. *Journal of Orthopaedic Science*, 14(5), 602–610.

Ivancic, P.C., Pearson, A.M., Panjabi, M.M. & Ito, S. (2004) Injury of the anterior longitudinal ligament during whiplash simulation. *European Spine Journal*, 13(1), 61–68.

Ivancic, P.C., Ito, S., Tominaga, Y., Rubin, W., Coe, M.P., Ndu, A.B., Carlson, E.J.& Panjabi, M.M. (2008) Whiplash causes increased laxity of cervical capsular ligament. *Clinical Biomechanic*, 23(2), 159–165.

Jakobsson, L. (1998) Automobile design and whiplash prevention. In: Gunzburg, R., Szpalski, M. (eds) Whiplash injuries: Current concepts in prevention, diagnosis and treatment of the cervical whiplash syndrome. Lippincott-Raven, Philadelphia, 299–306.

Jakobsson, L., Norin, H. & Svensson, M.Y. (2004) Parameters influencing AIS1 neck injury outcome in frontal impacts. *Traffic Injury Preventio*, 5(2), 156–163.

Jakobsson, L. (2004) Field analysis of AIS1 neck injuries in rear-end car impacts injury reducing effect of the WHIPS seat. *Journal of Whiplash and Related Disorders*, 3(2), 37–54.

Janssen, M.M., Drevelle, X., Humbert, L., Skalli, W. & Castelein, R.M. (2009) Differences in male and female spino-pelvic alignment in asymptomatic young adults and its relation to spinal deformities ‐ a three-dimensional analysis using upright low-dose digital biplanar X-rays. *Spine*, 34(23), E826-832.

Jonsson, H., Cesarini, K., Sahlstedt, B. & Rauschning, W. (1994) Findings and outcome in whiplash-type neck distortions. *Spine*, 19(24), 2733–2743.

Kaale, B.R., Krakenes, J., Alberktsen, G. & Wester, K. (2005) Whiplash-associated disorders impairment rating: neck disability index score according to severity of MRI findings of ligaments and membranes in the upper cervical spine. *Journal of Neurotrauma*, 22(4), 466-475.

Kaale, B.R., Krakenes, J., Alberktsen, G. & Wester, K. (2005) Head position and impact direction in whiplash injuries: associations with MRI-verified lesions of ligaments and membranes in the upper cervical spine. *Journal of Neurotrauma*, 22(11), 1294-1302.

Kaneoka, K., Ono, K., Inami, S. & Hayashi, K. (1999) Motion analysis of cervical vertebrae during whiplash loading. *Spine*, 24(8), 763-770.

Kaneoka, K., Ono, K., Inami, S. Ochiai, N. & Hayashi, K. (2002) The human cervical spine motion during rear impact collisions: a proposed cervical facet injury mechanism during whiplash trauma. *Journal of Whiplash and Related Disorders*, 1(1), 85-97.

Kasai, T., Ikata, T., Katoh, S., Miyake, R. & Tsubo, M. (1996) Growth of the cervical spine with special reference to its lordosis and mobility. *Spine*, 21(18), 2067-2073.

Katz, P.R., Reynolds, H.M., Foust, D.R. & Baum, J.K. (1975) Mid-sagittal dimensions of cervical vertebral bodies. *American Journal of Physical Anthropology*, 43(3), 319–326.

Kihlberg, J.K. (1969) Flexion-Torsion Neck Injury in Rear Impacts. In: *Association for the Advancement of Automobile Medicine*, Town, Country.

Kitagawa, Y., Yamada, K., Motojima, H. & Yasuki, T. (2015) Consideration on gender difference of whiplash associated disorder in low speed rear impact. In: *International Research Council on the Biomechanics of Injury Conference*, Lyon, France.

Klinich, K.D., Ebert, S.M., Van Ee C.A., Flannagan, C.A.C., Prasad, M., Reed, M.P. & Schneider, L.W. (2004) Cervical spine geometry in the automotive seated posture: variations with age, stature, and gender. *Stapp Car Crash Journal*, 48, 301-330.

Krafft, M. (2002) When do AIS1 neck injuries result in long-term consequences - Vehicle and human factors. *Traffic Injury Prevention*, 3(2), 89–97.

Krafft, M., Kullgren, A., Lie, A. & Tingvall, C. (2003) The risk of whiplash injury in the rear seat compared to the front seat in rear impacts. *Traffic Injury Prevention*, 4(2), 136–140.

Krakenes, J., Kaale, B., Moen, G., Nordli, H., Gilhus, N. & Rorvik, J. (2002) MRI assessment of the alar ligaments in the late stage of whiplash injury—a study of structural abnormalities and observer agreement. *Neuroradiology*, 44(7), 617–624.

Krakenes, J., Kaale, B., Moen, G., Nordli, H., Gilhus, N. & Rorvik, J. (2003) MRI of the tectorial and posterior atlanto-occipital membranes in the late stage of whiplash injury. *Neuroradiology*, 45(9), 585–91.

Krakenes, J., Kaale, B.R., Nordli, H., Moen, G., Rorvik, J. & Gilhus, N.E. (2003) MR analysis of the transverse ligament in the late stage of whiplash injury. *Acta Radiologica*, 44(6), 637–644.

Krakenes, J. & Kaale, B.R. (2006) Magnetic resonance imaging assessment of craniovertebral ligaments and membranes after whiplash trauma. *Spine*, 31(24), 2820–2826.

Kullgren, A. & Krafft, M. (2010) Gender analysis on whiplash seat effectiveness: results from real-world crashes. In: *International Research Council on the Biomechanics of Injury Conference*, Hanover, Germany.

Kullgren, A., Stigson, H. & Krafft, M. (2013) Development of whiplash associated disorders for male and female car occupants in cars launched since the 80s in different impact directions. In: *International Research Council on the Biomechanics of Injury Conference*, 2013, Gothenburg, Sweden.

Lee, J.H., Park, Y.K. & Kim, J.H. (2014) Chronic neck pain in young adults: perspectives on anatomic differences. *The Spine Journal*,14(11), 2628-2638.

Liguoro, D., Vandermeersch, B. & Guerin, J. (1994) Dimensions of cervical vertebral bodies according to age and sex. *Surgical Radiologic Anatomy*, 16(2), 149–155.

Lind, B., Sihlbom, H., Nordwall, A. & Malchau, H. (1989) Normal Range of Motion of the Cervical Spine. *Archives of Physical Medicine and Rehabilitation*, 70(9), 692–695.

Lindgren, K.A., Kettunen, J.A., Paatelma, M. & Mikkonen, R.H. (2009) Dynamic kinemagnetic resonance imaging in whiplash patients and in age- and sex-matched controls. *Pain Research and Management*, 14(6), 427–432.

Liliang, P.C., Lu, K., Hsieh, C-H., Kao, C.Y., Wang, K.W. & Chen HJ. (2008) Pulsed radiofrequency of cervical medial branches for treatment of whiplash-related cervical zygapophysial joint pain. *Surgical Neurology*, 70(Supp1), 50-55.

Linder, A., Carlsson, A., Svensson, M.Y. & Siegmund, G.P. (2008) Dynamic responses of female and male volunteers in rear impacts. *Traffic Injury Prevention*, 9(6), 592–599.

Liu, Y.K. & Dai, Q.G. (1989) The second stiffest axis of a beam-column: implications for cervical spine trauma. *Journal of Biomechanical Engineering*, 111(2), 122-127.

Lord, S.M., Barnsley, L., Wallis, B.J., McDonald, G.J. & Bogduk, N. (1996) Precutaneous radiofrequency neurotomy for chronic cervical zygapophysial joint pain. *The New England Journal of Medicine*, 335(23), 1721-1726.

Luan, F., Yang, K.H., Deng, B., Begeman, P.C., Tashman, S. & King, A.I. (2000) Qualitative analysis of neck kinematics during low-speed rear-end impact. *Clinical Biomechanics*, 15(9), 649-657.

Lundell, B., Jakobson, L., Alfredsson, B., Lindstrom, M. & Simonsson, L. (1998) The WHIPS Seat – A car seat for improved protection against neck injuries in rear end impacts. In: *Enhanced Safety of Vehicles Conference*, Windsor, Canada.

Maag, U., Desjardins, D., Bourbeau, R. & Laberge-Nadeau, C. (1990) Seat belts and neck injuries. In: *International Research Council on the Biomechanics of Injury Conference*, Bron, France.

MacNab, I. (1964) Acceleration injuries of the cervical spine. *Journal of Bone and Joint Surgery*, 46, 1797-1799.

Maiman, D.J., Sances, A.Jr., Myklebust, J.B., Larson, S.J., Houterman, C., Chilbert, M. & El-Ghatit, A.Z. (1983) Compression injury of the cervical spine. *Neurosurgery*, 13(3), 254-260.

Maiman, D.J., Yoganandan, N. & Pintar, F.A. (2002) Preinjury cervical alignment affecting spinal trauma. *Journal of Neurosurgery*, 97(1 Suppl), 57-62.

Matsumoto; M., Fujimura, Y., Suzuki, N., Toyama, Y. & Shiga, H. (1998) Cervical curvature in acute whiplash injures: prospective comparative study with asymptomatic subjects. *Injury*, 29(10), 775-778.

Matsushita, T., Sato, T., Hirabayashi, K. & Fujimura, S. (1994) X-Ray Study of the Human Neck Motion Due to Head Inertia Loading. *SAE Technical Paper*, No. 942208, 55-64.

Milne, N. (1991) The role of zygapophysial joint orientation and uncinated processes in controlling motion in the cervical spine. *Journal of Anatomy*, 178, 189-201.

Mordaka, J. (2004) *Finite element analysis of whiplash injury for women*. PhD., Nottingham Trent University, Nottingham, UK.

Morris, A.P., & Thomas, P.D. (1996) Neck injuries in the UK co-operative crash injury study. *SAE Technical Paper*, No.962433, 317-329.

Myran, R., Kvistad, K.A., Nygaard, O.P., Andresen, H., Folvik, M. & Zwart, J.A. (2008) Magnetic resonance imaging assessment of the alar ligaments in whiplash injuries: a case–control study. *Spine*, 33(18), 2012–2016.

Narragon, E.A. (1965) *Sex comparisons in automobile crash injury*. CAL Report No.VJ-1823-R15.

Newell, R.S., Siegmund, G.P., Blouin, J.S., Street, J. & Cripton, P.A. (2014) Cervical vertebral realignment when voluntarily adopting a protective neck posture. *Spine*, 39(15), E885-893.

Nibu, K., Cholewicki, J., Panjabi, M.M., Babat, L.B., Grauer, J.N., Kothe, R. & Dvorak, J. (1997) Dynamic elongation of the vertebral artery during an in vitro whiplash simulation. *European Spine Journal*, 6(4), 286-289.

Nygren, Å., Gustafsson, H. & Tingvall, C. (1985) Effects of different types of headrests in rear-end collisions. *International Conference on Experimental Safety Vehicles,* No. 856023, Oxford, UK

Ommaya, A.K., Faas, F. & Yarnell, P. (1968) Whiplash injury and brain damage: an experimental study. *Journal of American Medical Association*, 204(4), 285-289.

O'Neill, B., Haddon, W., Kelley, A.B. & Sorenson, W.W. (1972) Automobile head restraints—frequency of neck injury claims in relation to the presence of head restraints. *American Journal of Public Health*, 62(3), 399–406.

Ono, K., Kaneoka, K., Wittek, A. & Kajzer, J. (1997) Cervical injury mechanism based on the analysis of human cervical vertebral motion and head-neck-torso kinematics during low speed rear impacts. *SAE Technical Paper*, No. 973340, 339-356.

Ono, K., Inami, S., Kaneoka, K., Gotou, T., Kisanuki, T., Sakuma, S. & Miki, K. (1999) Relationship between localized spine deformation and cervical vertebral motions for low speed rear impacts using human volunteers. In: *International Research Council on the Biomechanics of Injury Conference* Barcelona, Spain.

Ono, K., Ejima, S., Suzuki, Y., Kaneoka, K., Fukushima, M. & Ujihshi, S. (2006) Prediction of neck injury risk based on the analysis of localized cervical vertebral motion of human volunteers during low-speed rear impacts. In: *International Research Council on the Biomechanics of Injury Conference*, Madrid, Spain.

Örtengren, T., Hansson, H.A., Lövsund, P., Svensson, M.Y., Suneson, A. & Saljo, A. (1996) Membrane leakage in spinal ganglion nerve cells induced by experimental whiplash extension motion: a study in pigs. *Journal of Neurotrauma*, 13(3), 171–180.

Otremski, I., Marsh, J.L., Wilde, B.R., McLardy Smith, P.D. & Newman R.J. (1989) Soft tissue cervical injuries in motor vehicle accidents. *Injury*, 20(6), 349–351.

Panjabi, M.M., Nibu, K. & Cholewicki, J. (1998a) Whiplash injuries and the potential for mechanical instability. *European Spine Journal*, 7(6), 484–492.

Panjabi, M.M., Cholewicki, J., Nibu, K., Grauer, J., Babat, L.B. & Dvorak, J. (1998b) Critical load of the human cervical spine: an in vitro experimental study. *Clinical Biomechanics*, 13(1), 239-49.

Panjabi, M.M., Cholewicki, J., Nibu, K., Babat, L.B. & Dvorak, J. (1998c) Simulation of whiplash trauma using whole cervical spine specimens. *Spine*, 23(1), 17-24.

Panjabi, M.M., Cholewicki, J., Nibu, K., Grauer, J. & Vahldiek, M. (1998d) Capsular ligament stretches during in vitro whiplash simulations. *Journal of Spine Disorders*, 11(3), 227-232.

Panjabi, M.M., Wang, J.L. & Delson, N. (1999) Neck injury criterion based on intervertebral motions and its evaluation using an instrumented neck dummy. In: *International Research Council on the Biomechanics of Injury Conference*, Sitges, Spain.

Panjabi, M.M., Ito, S., Pearson, A.M. & Ivancic, P.C. (2004) Injury mechanisms of the cervical intervertebral disc during simulated whiplash. *Spine*, 29(11), 1217–1225.

Parenteau, C.S., Zuby, D., Brolin, K.B., Svensson, M.Y., Palmertz, C. & Wang, S.C. (2013) Restrained male and female occupants in frontal crashes: Are we different? In: *International Research Council on the Biomechanics of Injury Conference*, Gothenburg, Sweden.

Parenteau, C.S., Zhang, P., Holcombe, S. & Wang, S. (2014) Characterization of vertebral angle and torso depth by gender and age groups with a focus on occupant safety. *Traffic Injury Prevention*, 15(1), 66-72.

Park, S.M., Song, K.S., Park, S.H., Kang, H., Riew, K.D. (2015) Does whole-spine lateral radiograph with clavicle positioning reflect the correct cervical sagittal alignments? *European Spine Journal*, 24(1), 57-62.

Pearson, A.M., Ivancic, P.C., Ito, S. & Panjabi, M.M. (2004) Facet Joint Kinematics and Injury Mechanisms During Simulated Whiplash. *Spine*, 29(4), 390–397.

Pettersson, K., Hildingsson, C., Toolanen, G., Fagerlund, M., & Bjornebrink, J. (1994) MRI and neurology in acute whiplash trauma. *Acta Orthopaedica Scandinavica*, 65(5), 525–8.

Pintar, F., Yoganandan, N., Voo, L., Cusick, J.F., Maiman, D.J. & Sances, A. Jr. (1995) Dynamic characteristics of the human cervical spine. *SAE Technical Paper*, No. 952722, 195-202.

Pramudita, J.A., Ono, K., Ejima, S., Kaneoka, K., Shiina, I. & Ujihashi, S. (2007) Head/neck/torso behavior and cervical vertebral motion of human volunteers during low speed rear impact: mini-sled tests with mass production car seat. In: *International Research Council on the Biomechanics of Research Conference*, Maastricht, The Netherlands.

Li, Q., Shen, H. & Li, M. (2013) Magnetic resonance imaging signal changes of alar and transverse ligaments not correlated with whiplash-associated disorders. *European Spine Journal*, 22(1), 14–20.

Radanov, B.P., Sturzenegger, M. & Di Stefano, G. (1995) Long-term outcome after whiplash injury. A 2-year follow-up considering features of injury mechanism and somatic, radiologic, and psychosocial findings. *Medicine*, 74(5), 281–297.

Richter, M., Otte, D., Pohlemann, T., Krettek, C. & Blauth, M. Whiplash-type neck distortion in restrained car drivers: frequency, causes and long-term results. *European Spine Journal*, 9(2), 109–117.

Ronnen, H.R., de Korte, P.J., Brink, P.R., van der Bijl, H.J., Tonino, A.J. & Franke, C.L. (1996) Acute whiplash injury: is there a role for MR imaging? A prospective study of 100 patients. *Radiology*, 201(1), 93-96.

Sato, F., Antona, J., Ejima, S. & Ono, K. (2010) Influence on cervical vertebral motion of the interaction between occupant and head restraint/seat, based on the reconstruction of rear-end collision using finite element human model. In: *International Research Council on the Biomechanics of Injury Conference*, Hanover, Germany.

Sato, F., Odani, M., Endo, Y., Tada, M., Miyazaki, Y., Nakajima, T., Ono, K., Morikawa, S. & Svensson, M.Y. (2016) Analysis of the alignment of whole spine in automotive seated and supine postures using an upright open MRI system. *International Journal of Automotive Engineering*, 7, 29-35.

Schonstrom, N., Twomey, L. & Taylor, J. (1993) The lateral atlanto-axial joints and their synovial folds: an in vitro study of soft tissue injuries and fractures. *The Journal of Trauma*, 35(6), 886-892.

Sekizuka, M. (1998) Seat designs for whiplash injury lessening. In: *Enhanced Safety of Vehicles Conference*, Windsor, Canada.

Schneider, L.W., Robbins, D.H, Pflüg, M.A. & Snyder, R.G. (1983) *Development of anthropometrically based design specifications for an advanced adult anthropomorphic dummy family.* Ann Arbor, MI, USA: University of Michigan Transportation Research Institute; Final Report, UMTRI-83-53-1.

Siegmund, G.P., King, D.J. & Lawrence, J.M. (1997) Head/neck kinematic response of human subjects in low-speed rear-end collisions. *SAE Technical Paper*, No. 973341.

Siegmund, G.P., Myers, B.S., Davis, M.B., Bohnet, H.F. & Winkelstein, B.A. (2001) Mechanical evidence of cervical facet capsule injury during whiplash: a cadaveric study using combined shear, compression and extension loading. *Spine*, 26(19), 2095–2101.

Spitzer, W.O., Skovron, M.L., Salmi, L.R., Cassidy, J.D., Duranceau, J., Suissa, S. & Zeiss, E. (1995) Scientific monograph of the Quebec task force on Whiplash-Associated Disorders: redefining "whiplash" and its management. *Spine*, 20(8 Suppl), 1-73.

Stemper, B.D., Yoganandan, N. & Pintar, F.A. (2003) Gender dependent cervical spine segmental kinematics during whiplash. *Journal of Biomechanics*, 36(9), 1281–1289.

Stemper, B.D., Yoganandan, N. & Pintar, F.A. (2004) Gender- and region-dependent local facet joint kinematics in rear impact. *Spine*, 29(16), 1764–1771.

Stemper, B.D., Yoganandan, N. & Pintar, F.A. (2005) Effects of abnormal posture on capsular ligament elongations in a computational model subjected to whiplash loading. *Journal of Biomechanics*, 38(6), 1313–1323.

Stemper, B.D., Yoganandan, N., Pintar, F.A., Maiman, D.J., Meyer, M.A, DeRosia, J., Shender, B.S. & Paskoff, G. (2008) Anatomical gender differences in cervical vertebrae of size-matched volunteers. *Spine*, 33(2), E44–E49.

Stemper, B.D., DeRosia, J., Yogananan, N., Pintar, F., Shender, B. & Paskoff, G. (2009) Gender dependent cervical spine anatomical differences in size-matched volunteers. *Biomedical Sciences Instrumentations*, 45, 149-154.

Stemper, B.D., Pintar, F.A. & Rao, R.D. (2011) The influence of morphology on cervical injury characteristics. *Spine*, 36(25S), S180–S186.

Stemper, B.D. & Corner, B.D. (2016) Whiplash-associated disorders: Occupant kinematics and neck morphology. *Journal of Orthopaedic & Sports Physical Therapy,* 46(10), 834-844.

Sterling, M. (2004) A proposed new classification system for whiplash associated disorders—implications for assessment and management. *Manual Therapy*, 9(2), 60–70.

Sterner, Y. & Gerdle, B. (2004) Acute and chronic whiplash disorders—a review. *Journal of Rehabilitation Medicine*, 36(5), 193–209.

Storvik, S.G., Stemper, B.D., Yoganandan, N. & Pintar, FA. (2009) Population-based estimates of whiplash injury using NASS CDS data–biomed 2009. *Biomedical Sciences Instrumentation*, 45, 244–249.

Sturzenegger, M., Radanov, P.B. & Di Stefano, G. (1995) The effect of accident mechanisms and initial findings on the long-term course of whiplash. *Journal of Neurology*, 242(7), 443-449.

Svensson, M.Y., Aldman, B., Hansson, H.A., Lövsund, P., Seeman, T., Suneson, A. & Örtengren, T. (1993) Pressure effects in the spinal canal during whiplash extension motion: a possible cause of injury to the cervical spinal ganglia. In: *International Research Council on the Biomechanics of Injury Conference*, Eindhoven, Netherlands.

Svensson, M.Y., Lövsund, P., Håland, Y. & Larsson, S. (1993) Rear-end collisions—A study of the influence of backrest properties on head-neck motion using a new dummy neck. *SAE Technical Paper*, No. 930343.

Szabo, T.J., Welcher, J.B., Anderson, R.D. & Rice, M. (1994) Human occupant kinematic response to low-speed rear end impacts. *SAE Technical Paper*, No. 940432, 23-35.

Takeshima, T., Omokawa, S., Takaoka, T., Araki, M., Ueda, Y. & Takakura, Y. (2002) Sagittal alignment of cervical flexion and extension. *Spine*, 27(15), E348–E355.

Taylor, J.R. & Twomey, L.T. (1993) Acute injuries to cervical joints. An autopsy study of neck sprain. *Spine*, 18(9), 1115–1122.

Taylor, J.R. & Taylor, M. (1996) Cervical spinal injuries: an autopsy study of 109 blunt injuries. *Journal of Musculoskeletal Pain*, 4(4), 61–80.

Temming, J. & Zobel, R. (1998) Frequency and risk of cervical spine distortion injuries in passenger car accidents: significance of human factors data. In*: International Research Council on the Biomechanics of Injury Conference*, 1998, Gothenburg, Sweden.

Thomas, C., Faverjon, G., Hartemann, F., Tarriere, C., Patel, A. & Got, C. (1982) Protection against rear-end accidents. In: *International Research Council on the Biomechanics of Injury Conference,* Cologne, Germany.

Toyota Motor Corporation, (2011) *Documentation - Total Human Model for Safety (THUMS) - AF50 occupant model: Version 4.0_211103*, Nagakute, Aichi, Japan.

Uhrenholt, L., Grunnet-Nilsson, N. & Hartvigsen, J. (2002) Cervical spine lesions after road traffic accidents. A systematic review. *Spine*, 27(17), 1934–1941.

Valkeinen, H., Ylinen, J., Malkia, E., Alen, M. & Hakkinen, K. (2002) Maximal force, force/time and activation/coactivation characteristics of the neck muscles in extension and flexion in healthy men and women at different ages. *European Journal of Applied Physiology*, 88(3), 247–254.

Vasavada, A., Li, S. & Delp. S. (2001) Three-Dimensional Isometric Strength of Neck Muscles in Humans. *Spine.* 26(17), 1904-1909.

Vasavada, A.N., Danaraj, J. & Siegmund, G.P. (2008) Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics*, 41(1), 114–121.

Vetti, N., Krakenes, J., Damsgaard, E., Rorvik, J., Gilhus, N.E. & Espeland, A. (2011) Magnetic resonance imaging of the alar and transverse ligaments in acute whiplash-associated disorders 1 and 2: a cross-sectional controlled study. *Spine*, 36(6), E434–E440.

Watanabe, Y., Ichikawa, H., Kayama, O., Ono, K., Kaneoka, K. & Inami, S. (2000) Influence of seat characteristics on occupant motion in low-velocity rear-end impacts. *Accident Analysis and Prevention*, 32(2), 243-250.

Watkinson, A., Gargan, M.F. & Bannister, G.C. (1991) Prognostic factors in soft tissue injuries of the cervical spine. *Injury*, 22(4), 307-309.

White, N.A., Begeman, P.C., Hardy, W.N., Yang, K.H., Ono, K., Sato, F., Kamiji, K., Yasuki, T. & Bey, M.J. (2009) Investigation of upper body and cervical spine kinematics of post mortem human subjects (PMHS) during low‐speed, rear‐end impacts. SAE Technical Paper, No. 2009‐01‐0387.

Wiklund K. & Larsson, H. (1997) SAAB active head restraint (SAHR) – seat design to reduce the risk of neck injuries in rear impacts. *SAE Technical Paper*, No. 980297.

Wilmink J.T. & Patijn, J. (2001) MR imaging of alar ligament in whiplash-associated disorders: an observer study. *Neuroradiology*, 43(10), 859–863

Winkelstein, B.A., Nightingale, R.W., Richardson, W.J. & Myers, B.S. (2000) The cervical facet capsule and its role in whiplash injury: a biomechanical investigation. *Spine*, 25(10), 1238–1246.

Yang, K.H. & King, A.I. (2003) Neck kinematics in rear-end impacts. *Pain Research and Management,* 8(2), 79–85.

Yao, H.D., Svensson, M.Y. & Nilsson, H. (2016) Transient pressure changes in the vertebral canal during whiplash motion –a hydrodynamic modelling approach. *Journal of Biomechanics*, 49(3), 416-422.

Yoganandan, N., Sances, A. Jr., Maiman, D.J., Myklebust, J.B., Pech, P. & Larson, S.J. (1986) Experimental spinal injuries with vertical impact. *Spine*, 11(9), 855–860.

Yoganandan, N., Pintar, F.A., Gennarelli, T.A., Eppinger, R.H. & Voo, L.M. (1999) Geometrical effects on the mechanism of cervical spine injury due to head impact. In: *International Research Council of the Biomechanics of Injury Conference*, Sitges, Spain.

Yogananadan, N., Pintar, F.A., Stemper, B.D. & Schlick, M.B. (2000) Biomechanics of human occupants in simulated rear crashes: Documentation of neck injuries and comparison of injury criteria. *Stapp Car Crash Journal*, 44, 189-204.

Yoganandan, N., Cusick, J.F., Pinter, F.A., Rao, R.D. (2001) Whiplash injury determination with conventional spine imaging and cryomicrotomy. *Spine*, 26(22), 2443–2448.

Yoganandan, N., Pinter, F.A., Cusick, J.F. (2002) Biomechanical analyses of whiplash injuries using an experimental model. *Accident Analysis and Prevention*, 34(5), 663–671.

Youdas, J.W., Garrett, T., Suman, V.J., Bogard, C.L., Hallman, H.O. & Carey, J.R. (1992) Normal range of motion of the cervical spine: an initial goniometric study. *Physical Therapy*, 72(11), 770–80.

Yukawa, Y., Kato, F., Suda, K., Yamagata, M. & Ueta, T. (2012) Age-related changes in osseous anatomy, alignment, and range of motion of the cervical spine. Part I: radiographic data from over 1,200 asymptomatic subjects. *European Spine Journal*, 21(8), 1492–1498.